

Development of Models to Predict Tensile Strength of Cotton Woven Fabrics

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ABSTRACT

Tensile strength has been accepted as one of the most important performance attributes of woven textiles. In this work, multiple linear regression models are developed by using empirical data for the prediction of woven fabric tensile strength manufactured from cotton yarns. Tensile strength of warp & weft yarns, warp & weft fabric density, and weave design were used as input parameters to determine warp- and weft-way tensile strength of the woven fabrics. The developed models are able to predict the fabric strength with very good accuracy. Warp yarn strength and ends per 25 mm are found to be the most dominant factors influencing fabric strength in warp direction while weft yarn strength and picks per 25 mm are most vital in weft direction.

INTRODUCTION

Tensile strength of a yarn or fabric is defined as a maximum load that it will endure without breaking when subjected to uniaxial tensile loading. Tensile strength of a woven fabric is one of the most important properties which make it superior in many applications as compared to non-woven and knitted fabrics. Literature review reveals that the tensile strength of a woven fabric not only depends on the strength of the constituent yarns, but also on many other factors including yarn linear density, yarn twist per unit length, twist direction, yarn structure as influenced by the spinning system, yarn bending behavior, coefficient of friction and initial modulus of the yarn, fabric geometry, warp and weft density, weave design or yarn interlacement pattern, weaving conditions (such as temperature, humidity and yarn tensions during weaving) as well as fabric finishing treatments [1, 2, 3, 4].

Over the past seventy five years, a number of attempts have been made to develop various models for the analysis and prediction of tensile properties of woven fabrics. Peirce developed a geometrical model

in 1937 for plain-woven fabrics [5], which was further refined and extended by Love [6] who described graphical relationships in cloth geometry for plain, twill and satin weaves. In 1959, Taylor [7] used a mechanical model based on Peirce's geometrical model to examine the tear strength of a woven fabric as a function of yarn strength and the force required to slip one yarn set over another. Models developed by Olofsson [8] and Kawabata [3] further added to the understanding of fabric tensile deformation process. However, a basic limitation of the geometrical models has been that the geometry of the fabric is described by a combination of lines, arcs and circles, and that the yarns within the fabric are assumed to be perfectly uniform, incompressible, completely flexible and circular in cross-section, which is actually not the case in most real fabrics.

De Jong and Postle's energy method also assumed uniform tensile properties of the constituent yarns, which actually show variation in tensile strength and do not break simultaneously in a tensioned fabric [9, 10]. Later models of Baser [11, 12], Sun [13], Hamilton [14], Leaf and Anandjiwala [15] were also based on similar assumptions, thus the prediction accuracy of these models was also limited. Shahpurwala and Schwartz [16] used the statistical bundle theory to predict the strength of plain-woven fabrics. However, the prediction values were always lower than the actual ones because the model failed to take into account the effect of yarn interaction at cross-over points. The chain-of-bundles model was further refined by Chen and Ding [17]. However, the prediction accuracy of the model was still not very good.

Recently, Artificial Neural Network (ANN) and regression based models for predicting the tensile strength of woven fabrics have been developed by Majumdar, based on the empirical data of 33 fabrics [18]. The prediction accuracy of these models is quite

promising, because these models are based on empirical data of real fabrics. However, these models are valid only for plain woven fabrics and for a narrow range of fabric specifications. The objective of this research work is to develop empirical models based on wider range of fabric specifications which are valid both for plain-woven and longer float fabrics.

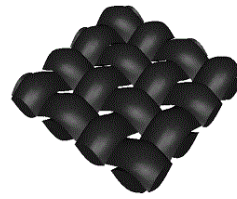


FIGURE 1a. Plain weave.

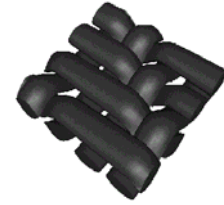


FIGURE 1b. Twill weave.

METHODS

One hundred and thirty five fabric samples each in plain (float length = 1) and twill weave (float length = 3) were woven on a Sulzer projectile weaving machine (P 7150) according to the constructions given in *Table I*. The structure of plain and twill weave is depicted in *Figure 1a & b*.

All the samples were desized by enzymatic method because unlike oxidative or acidic desizing, it would not cause any loss in fabric strength. After desizing, all the fabric samples were first preconditioned at a temperature of 47°C and relative humidity of 10 to 25 % for 4 hours in a hot air oven and then conditioned for 24 hours in standard atmosphere in accordance with ISO 139:2005.

TABLE I: Constructions used for making fabrics in plain and twill (3/1) designs.

S. No.	Set 1*	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
1	20×20/ 40×40	20×25/ 40×40	20×30/ 40×40	25×20/ 40×40	25×25/ 40×40	25×30/ 40×40	30×20/ 40×40	30×25/ 40×40	30×30/ 40×40
2	20×20/ 50×40	20×25/ 50×40	20×30/ 50×40	25×20/ 50×40	25×25/ 50×40	25×30/ 50×40	30×20/ 50×40	30×25/ 50×40	30×30/ 50×40
3	20×20/ 50×50	20×25/ 50×50	20×30/ 50×50	25×20/ 50×50	25×25/ 50×50	25×30/ 50×50	30×20/ 50×50	30×25/ 50×50	30×30/ 50×50
4	20×20/ 60×40	20×25/ 60×40	20×30/ 60×40	25×20/ 60×40	25×25/ 60×40	25×30/ 60×40	30×20/ 60×40	30×25/ 60×40	30×30/ 60×40
5	20×20/ 60×50	20×25/ 60×50	20×30/ 60×50	25×20/ 60×50	25×25/ 60×50	25×30/ 60×50	30×20/ 60×50	30×25/ 60×50	30×30/ 60×50
6	20×20/ 60×60	20×25/ 60×60	20×30/ 60×60	25×20/ 60×60	25×25/ 60×60	25×30/ 60×60	30×20/ 60×60	30×25/ 60×60	30×30/ 60×60
7	20×20/ 70×40	20×25/ 70×40	20×30/ 70×40	25×20/ 70×40	25×25/ 70×40	25×30/ 70×40	30×20/ 70×40	30×25/ 70×40	30×30/ 70×40
8	20×20/ 70×50	20×25/ 70×40	20×30/ 70×50	25×20/ 70×40	25×25/ 70×50	25×30/ 70×50	30×20/ 70×50	30×25/ 70×50	30×30/ 70×50
9	20×20/ 70×60	20×25/ 70×60	20×30/ 70×40	25×20/ 70×60	25×25/ 70×60	25×30/ 70×60	30×20/ 70×60	30×25/ 70×60	30×30/ 70×60
10	20×20/ 70×70	20×25/ 70×70	20×30/ 70×70	25×20/ 70×70	25×25/ 70×70	25×30/ 70×70	30×20/ 70×70	30×25/ 70×70	30×30/ 70×70
11	20×20/ 80×40	20×25/ 80×40	20×30/ 80×40	25×20/ 80×40	25×25/ 80×40	25×30/ 80×40	30×20/ 80×40	30×25/ 80×40	30×30/ 80×40
12	20×20/ 80×50	20×25/ 80×50	20×30/ 80×50	25×20/ 80×50	25×25/ 80×50	25×30/ 80×50	30×20/ 80×50	30×25/ 80×50	30×30/ 80×50
13	20×20/ 80×60	20×25/ 80×60	20×30/ 80×60	25×20/ 80×60	25×25/ 80×60	25×30/ 80×60	30×20/ 80×60	30×25/ 80×60	30×30/ 80×60
14	20×20/ 80×70	20×25/ 80×70	20×30/ 80×70	25×20/ 80×70	25×25/ 80×70	25×30/ 80×70	30×20/ 80×70	30×25/ 80×70	30×30/ 80×70
15	20×20/ 80×80	20×25/ 80×80	20×30/ 80×80	25×20/ 80×80	25×25/ 80×80	25×30/ 80×80	30×20/ 80×80	30×25/ 80×80	30×30/ 80×80

*Fabric constructions are given as: warp linear density x weft linear density (tex) /ends x picks (per 25mm)

Test specimens were prepared and tensile strength was determined both in warp and weft directions according to ISO standard test method 13934-1: 1999. Calibrated universal strength tester (M-250 made by SDL, UK) was used for determining the fabric tensile strength at a gauge length of 200 mm and an extension speed of 100 mm/min. Similarly, ends and picks per 25 mm of each sample were determined using standard testing method of ISO 7211-2:1984.

Tensile properties of yarns were measured by Uster Tensorapid-4 in accordance with ISO 2062:1993 test method at a gauge length of 500 mm and an extension speed of 5000 mm/min.

Similarly, linear density of warp and weft yarns was also measured according to ISO 2060:1994 test method. From the available 270 data sets of yarn and fabric, 234 data sets were used for the development of warp and weft way linear regression equations. Remaining 36 data sets (18 of plain weave + 18 of twill weave) were used to evaluate the performance of the developed relationships. All statistical analyses were done using Minitab statistical software.

RESULTS

Development of Models

Best subset regression models are given in *Table II*. Warp yarn strength (YS_{wp}), weft yarn strength (YS_{wt}), ends per 25mm (E), picks per 25mm (P) and float length (FL) were used as predictor variables while R^2 , R^2 (Adj), C-P and s are statistical terms used for model selection criteria. Models with the highest R^2 and adjusted R^2 , smallest s, and C-p close to the number of predictors (variables) are considered as best models. Accordingly, models at S. No: 9 for both directions given in *Table II* were selected for further analysis using response surface regression technique.

End results of response surface regression analysis are consolidated in *Tables III and IV*. The regression coefficients given in *Table III* are based on coded units of the variables used by the Minitab software. Use of coded units helps to eliminate any spurious statistical results due to different measurement scales of the factors and makes them easy to interpret. For each factor level measured in the original scale, the coded unit can be obtained by using the following expression:

TABLE II: Best subsets of regression models.

	S. No	Variables	R^2	R^2 (Adj)	C-P	s	YS_{wp}	YS_{wt}	E	P	FL
For warp-way fabric strength	1	1	58.2	58.1	2681.3	90.430	-	-	x	-	-
	2	1	36.9	36.6	4171.4	111.19	x	-	-	-	-
	3	2	95.1	95.1	112.4	30.989	x	-	x	-	-
	4	2	59.2	58.9	2614.9	89.555	-	-	x	-	x
	5	3	96.1	96.0	46.0	27.763	x	-	x	-	x
	6	3	95.6	95.6	79.0	29.395	x	-	x	x	-
	7	4	96.6	96.5	12.6	25.948	x	-	x	x	x
	8	4	96.2	96.2	39.4	27.380	x	x	x	-	x
	9	5	96.7	96.7	6.0	25.528	x	x	x	x	x
For weft-way fabric strength	1	1	69.1	69.0	1625.3	69.724	-	-	-	x	-
	2	1	25.5	25.2	4247.4	108.31	-	x	-	-	-
	3	2	94.6	94.6	95.1	29.159	-	x	-	x	-
	4	2	70.2	69.9	1562.9	68.651	-	-	-	x	x
	5	3	95.7	95.6	32.7	26.148	-	x	-	x	x
	6	3	95.0	95.0	71.6	28.046	-	x	x	x	-
	7	4	96.1	96.1	9.2	24.880	-	x	x	x	x
	8	4	95.8	95.7	29.5	25.943	x	x	-	x	x
	9	5	96.2	96.1	6.0	24.656	x	x	x	x	x

Coded unit = (Original factor level \times 2 - Max. level - Min. level) / (Max. level - Min. level)

Thus final models for warp and weft wise fabric strength can be written by using factor coefficients given in *Table III* as follows:

$$FTS_{wp} = 398.82 + 87.61y_{swp} + 5.99y_{swt} + 165.05e + 17.55p - 13.8fl + 43.87e^*y_{swp} \quad (1)$$

$$FTS_{wt} = 370.95 + 2.96y_{swp} + 91.91y_{swt} + 14.47e + 152.9p - 13.51fl + 42.43p^*y_{swt} \quad (2)$$

Where FTS_{wp} is the fabric tensile strength in warp direction (N); FTS_{wt} is the fabric tensile strength in weft direction (N); $y_{s_{wp}}$ is the coded value of warp yarn strength; $y_{s_{wt}}$ is the coded value of weft yarn strength; e is the coded value of ends/25mm; p is the coded value of picks/25mm and fl is the coded value of float length.

Eq. (1) and Eq. (2) can be used to calculate the predicted response by putting in the coded values of the predictor variables. Because the coefficients were estimated using coded units, putting uncoded factor values into this equation would generate incorrect predictions.

TABLE III: Estimated regression coefficients (coded) for factors of selected models.

	S. No	Terms	Coefficient	SE Coefficient	T	P
For warp –way fabric strength	1	Constant	398.82	0.7644	521.712	0.000
	2	$y_{s_{wp}}$	87.61	0.6892	127.118	0.000
	3	$y_{s_{wt}}$	5.99	0.6618	9.058	0.000
	4	e	165.05	0.9867	167.282	0.000
	5	p	17.55	0.9569	18.336	0.000
	6	fl	-13.80	0.5404	-25.535	0.000
	7	$e^*y_{s_{wp}}$	43.87	0.9940	44.132	0.000
R-Sq = 99.7% R-Sq(adj) = 99.6%						
For weft –way fabric strength	1	Constant	370.95	0.8274	448.310	0.000
	2	$y_{s_{wp}}$	2.96	0.6891	4.290	0.000
	3	$y_{s_{wt}}$	91.91	0.8199	112.101	0.000
	4	e	14.47	1.0542	13.730	0.000
	5	p	152.90	1.0376	147.365	0.000
	6	fl	-13.51	0.5859	-23.061	0.000
	7	$p^*y_{s_{wt}}$	42.43	1.1047	38.404	0.000
R-Sq = 99.5% R-Sq(adj) = 99.5%						

TABLE IV: Analysis of variance for factors of selected models.

	S. No	Source	DF	Seq SS Coefficient	Adj SS	Adj MS	F	P
For warp –way fabric strength	1	Regression	6	4528165	4528165	754694	1E+04	0.000
	2	Linear	5	4395094	4244855	848971	1E+04	0.000
	3	Interaction	1	133072	133072	133072	2E+03	0.000
	4	Residual Error	227	15510	15510	68		
	5	Total	233	4543675				
For weft-way fabric strength	1	Regression	6	3615264	3615264	602544	8E+03	0.000
	2	Linear	5	3496777	3587870	717574	9E+03	0.000
	3	Interaction	1	118487	118487	118487	1E+03	0.000
	4	Residual Error	227	18237	18237	80		
	5	Total	233	3633500				

The statistics presented in *Table III and IV* indicates highly significant models (P-value<0.05) for response variable, i.e., fabric strength, both in warp and weft directions. It is evident from the coefficients that all predictor variables have a positive effect on the fabric tensile strength except the float length. The higher the fabric float length, lower the fabric strength. In other words, the fabric strength of plain weave is higher as compared to 3/1 twill fabrics.

This can be explained as: In plain design, warp and weft yarns are interlaced one up and one down, while in twill 3/1 design both yarns are interlaced by the order of three up and one down in the face and back of fabric. This difference of interlacement changes the contact area between warp and weft yarns. So contact friction between warp and weft yarns of plain samples is more than twill samples. This higher friction provides more resistance to tensile load. It

means structure of twill samples having same construction as plain samples is loose and has less binding effect of cross yarns due to float length. Hence tensile strength of twill weave design is less than plain weave.

The values of coefficients further indicate that number of ends per 25 mm has the most profound effect on warp-wise fabric strength, followed by warp yarn strength while the effect of weft yarn strength is least among the predictor variables. As far as weft-wise fabric strength is concerned, it is affected most by number of picks, followed by weft yarn strength and least effected by warp yarn strength. R^2 and R^2 (adjusted) values for the developed models indicate that more than 99 % of the variation present in observed fabric strength, explained by predictor variables, has been included in the model which indicates very high prediction ability of the developed model.

The modified regression models using uncoded values of the coefficients are given as Eq. (3) and Eq. (4). These equations can be used to calculate the predicted warp and weft wise fabric strength by directly putting in the uncoded real values of tensile strength of warp and weft yarns (cN), ends/25mm, picks/25mm and float length.

$$FTS_{wp} = 55.01 - 0.5YS_{wp} + 0.06YS_{wt} - 1.85E + 0.88P - 13.8FL + 0.025E*YS_{wp} \quad (3)$$

$$FTS_{wt} = 37.1 + 0.03YS_{wp} - 0.38YS_{wt} + 0.72E - 1.64P - 13.5FL + 0.023P*YS_{wt} \quad (4)$$

Eq. (1) contains an interaction term of warp yarn strength and ends per 25 mm while Eq. (2) contains an interaction term of weft yarn strength and picks per 25 mm. These interaction plots can be made to compare the relative effects across these factors.

To plot the interaction factors and response, surface wire frame technique was used which displayed a three-dimensional view and provided a clear picture of the response surface. Response surface wire frame regarding the interaction terms in Eq. (1) and Eq. (2) are given in *Figure 2*.

It is evident from *Figure 2* that increase in warp-wise fabric strength (FTS_{wp}) is much sharper when warp yarn strength is higher along with more number of ends per 25 mm than those at low warp yarn strength values. Similarly, increase in weft-wise fabric strength (FTS_{wt}) is much sharper when weft yarn strength is higher along with more number of picks per 25 mm than those at low weft yarn strength values.

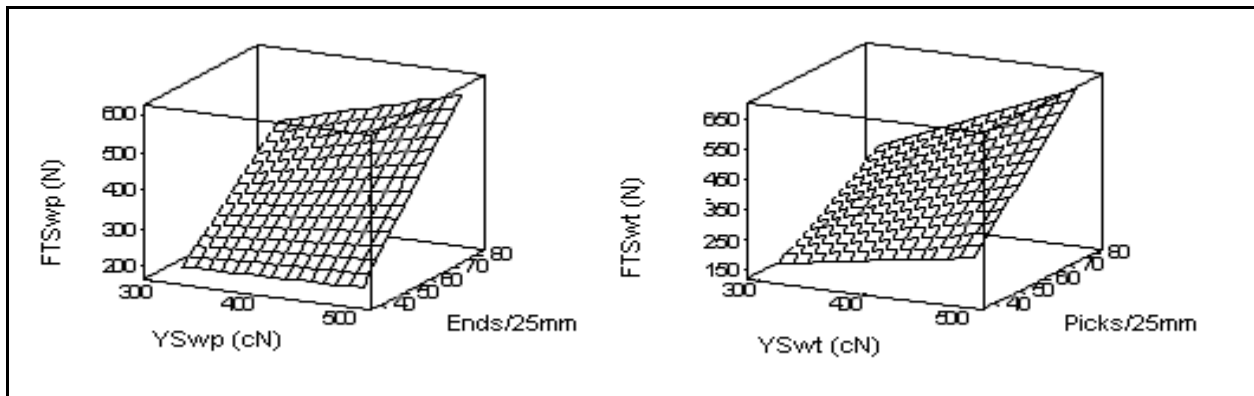


FIGURE 2: Surface wire frame plot for interaction terms of FTS_{wp} and FTS_{wt} .

Validation of Developed Models

As mentioned above, out of a total number of 270 samples, the data sets of 234 samples were used to develop the models for the prediction of fabric tensile strength, while data sets of 36 samples (18 of plain weave + 18 of twill weave) were used to check the validity of the developed models. Comparison of observed fabric strength values and those predicted by Eq. (1) and Eq. (2) is given in *Tables V and VI*. Fitted line plots between observed and predicted

values are given in *Figure 3*. Pearson correlation between observed and predicted values of warp wise fabric strength is 0.976 and of weft wise strength is 0.975 with P-value of 0.000 indicating a very strong ability and accuracy of the model.

CONCLUSIONS

Multiple linear regression models for tensile strength of fabric in warp and weft direction were developed successfully by using the empirical data of yarns and

234 woven fabric samples carefully manufactured from cotton yarn.

The prediction ability and accuracy of the developed models was assessed by correlation analysis of the predicted and actual warp and weft fabric strip strength values. The Pearson correlations between the actual and the predicted strength for warp and weft were found to be 0.976 and 0.975 respectively with a p-value of 0.000 indicating a very strong ability and accuracy of the equations. It is concluded that tensile strength of cotton fabric can be accurately predicted

with the help of these developed multiple linear regression models using warp and weft yarn strength, ends and picks per 25 mm and float length as predictor variables. The models developed in this study are valid for woven cotton fabrics of upto 3 float length, with warp and weft linear densities ranging from 20-30 tex, while ends and picks per 25mm ranging from 40-80. The study may be extended in future to include other linear densities and wider range of ends and picks per 25mm, as well as for various other fibres, blends and fabric constructions.

TABLE V: Actual and predicted warp wise fabric strength.

Sample Construction	Plain (1/1) Fabric Samples		Absolute Error (%)	Twill (3/1) Fabric Samples		Absolute Error (%)
	Observed FTS _{wp} (N)	Predicted FTS _{wp} (N)		Observed FTS _{wp} (N)	Predicted FTS _{wp} (N)	
20×20/70×50	375	375	0.09	366	347	5.17
20×20/80×60	443	445	0.39	421	417	0.92
20×25/70×60	408	389	4.56	367	362	1.42
20×25/80×50	434	442	1.81	440	414	5.85
20×30/70×50	400	387	3.34	363	359	1.09
20×30/80×70	460	465	1.19	436	438	0.43
25×20/70×60	431	437	1.44	402	410	1.90
25×20/80×50	500	500	0.08	447	473	5.78
25×25/70×50	411	434	5.68	412	407	1.28
25×25/80×70	502	524	4.37	472	496	5.16
25×30/70×60	442	449	1.63	410	422	2.83
25×30/80×60	528	521	1.29	471	494	4.80
30×20/70×50	596	595	0.22	566	567	0.19
30×20/80×70	703	718	2.07	676	690	2.06
30×25/70×60	598	609	1.90	584	582	0.38
30×25/80×60	720	715	0.74	684	687	0.44
30×30/70×50	613	607	1.04	578	579	0.18
30×30/80×50	707	712	0.69	676	684	1.23
Mean absolute error (%)			1.81	---		2.28

TABLE VI: Actual and predicted weft wise fabric strength.

Sample Construction	Plain (1/1) Fabric Samples		Absolute Error (%)	Twill (3/1) Fabric Samples		Absolute Error (%)
	Observed FTS _{wt} (N)	Predicted FTS _{wt} (N)		Observed FTS _{wt} (N)	Predicted FTS _{wt} (N)	
20×20/70×50	226	242	7.04	209	215	2.65
20×20/80×60	286	304	6.20	270	277	2.61
20×25/70×60	380	389	2.42	353	362	2.53
20×25/80×50	319	320	0.06	298	293	1.97
20×30/70×50	388	383	1.27	352	356	1.03
20×30/80×70	606	586	3.35	547	559	2.05
25×20/70×60	290	300	3.48	287	273	4.97
25×20/80×50	237	252	6.37	227	225	0.94
25×25/70×50	314	315	0.30	282	288	2.29
25×25/80×70	485	475	2.03	435	448	3.05
25×30/70×60	500	484	3.33	443	457	3.07
25×30/80×60	511	491	3.90	450	464	3.07
30×20/70×50	240	248	3.06	224	220	1.41
30×20/80×70	379	365	3.54	341	338	0.76
30×25/70×60	402	395	1.93	361	368	1.98
30×25/80×60	416	402	3.29	369	375	1.65
30×30/70×50	380	389	2.38	369	362	1.81
30×30/80×50	394	396	0.51	369	369	0.07
Mean absolute error (%)			3.03	---		2.11

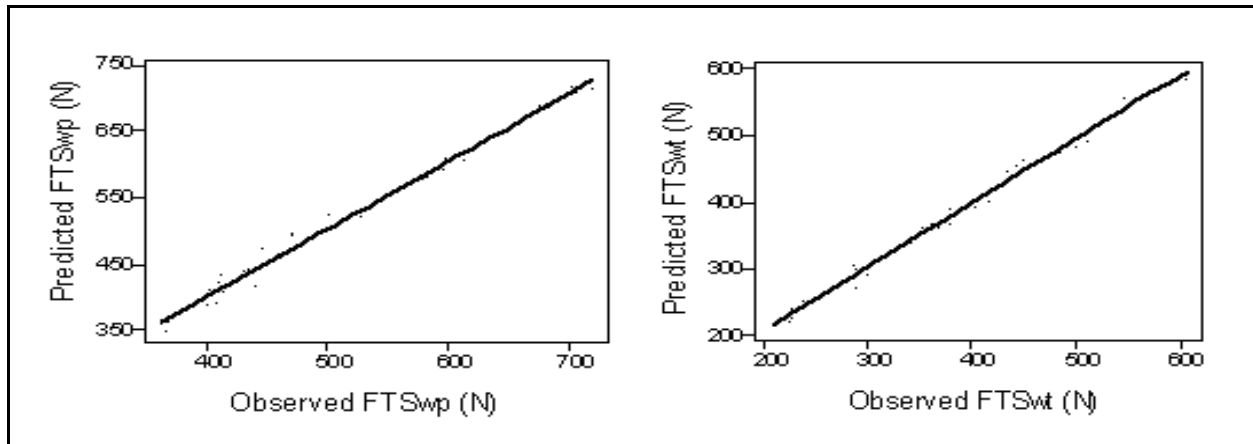


FIGURE 3: Fitted line plot between actual and predicted FTS_{wp} and FTS_{wt} .

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